DATASET FROM LONG-TERM AIR QUALITY MONITORING IN THE WORLD NATURAL HERITAGE GEIRANGERFJORD, WESTERN NORWAY (AQM-G)

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With 4 figures, 1 table and 1 data supplement
Received 09 September 2023 · Accepted 22 September 2023

Summary: Here, we present a datapaper containing observational air quality and meteorological data related to our long-term air quality monitoring program at the UNESCO Natural World Heritage Area Geirangerfjord, Western Norway. The dataset will be updated with future data.

Zusammenfassung: Dies ist eine Datenpublikation gemessener Luftqualitäts- und meteorologischer Variablen basierend auf unserem langfristigen Luftqualitätsüberwachungsprogramm in der UNESCO Weltnaturerbestätte Geirangerfjord, Westnorwegen. Die Datenbank wird zukünftig fortlaufend aktualisiert.

Keywords: Particulate matter, air pollution, cruise ship emissions, microclimate

1 Background, objectives and hypothesis

According to a recent review by Giovannini et al. (2020), one of the most serious hazards in mountainous areas with complex terrain involves pollutant emissions and their effects on air quality. As emphasized by several authors (Eckhardt et al. 2013, Largeron a. Staquet 2016, Quimbayo-Duarte et al. 2021), complex terrain significantly affects the spatiotemporal distribution and concentration patterns of air pollutants, i.e., due to inversion layer formation hindering vertical air exchange. While many areas experience reduced air quality from miscellaneous emission sources due to the presence of topographic features in complex terrain (Wallace et al. 2010, Zhan et al. 2023), those at the coast may in particular be substantially affected by marine traffic emissions (Mölders et al. 2010). Especially concentrations of particulate matter (PM) on land were found to be considerably increased due to ship traffic (Corbett et al. 2007, Eyring et al. 2010, Contini et al. 2021).

Against this background, we here present data of our long-term air quality monitoring program in the UNESCO Natural World Heritage Area Geirangerfjord, Western Norway (Fig. 1), where one of the most visited and important cruise ports of Norway is located (Johansen 2021, Geirangerfjord Cruise Port n.d.). Particularly from April to October, Geirangerfjord is heavily frequented by cruise ships and two narrow hillside roads on land, resulting in a total number of 985,653 tourists in 2018 (Yttredal et al. 2019, Yttredal & Homlong 2019). The local mountain climatology in the area is complex: i.e., radiation-determined thermal air convection, cold air streams and accumulation, and foehn effects, serve as the main drivers for the spatial distribution of pollutants in the specific topography. From a broad perspective, our study area provides ideal methodological conditions to investigate the characteristics of ship-related PM in complex terrain. The objective of our monitoring program is to understand the sources, the quantities, and the mechanisms of the spatiotemporal distribution of particulate matter with its specific climatic driving forces in a long-term perspective. Corresponding to the complex terrain, we presumed that specific constellations of topography and weather may lead to cumulative effects of ship-related PM in our study area, which is why we particularly scrutinized the atmospheric residence time of PM.

2 Methods and techniques

The experimental setting of our long-term air quality monitoring program is related to our long-term alpine ecosystem research program in central Norway (LTAER-NO; Löffler & Pape 2020),

https://doi.org/10.3112/erdkunde.2023.dp.03 eISSN 2702-5985

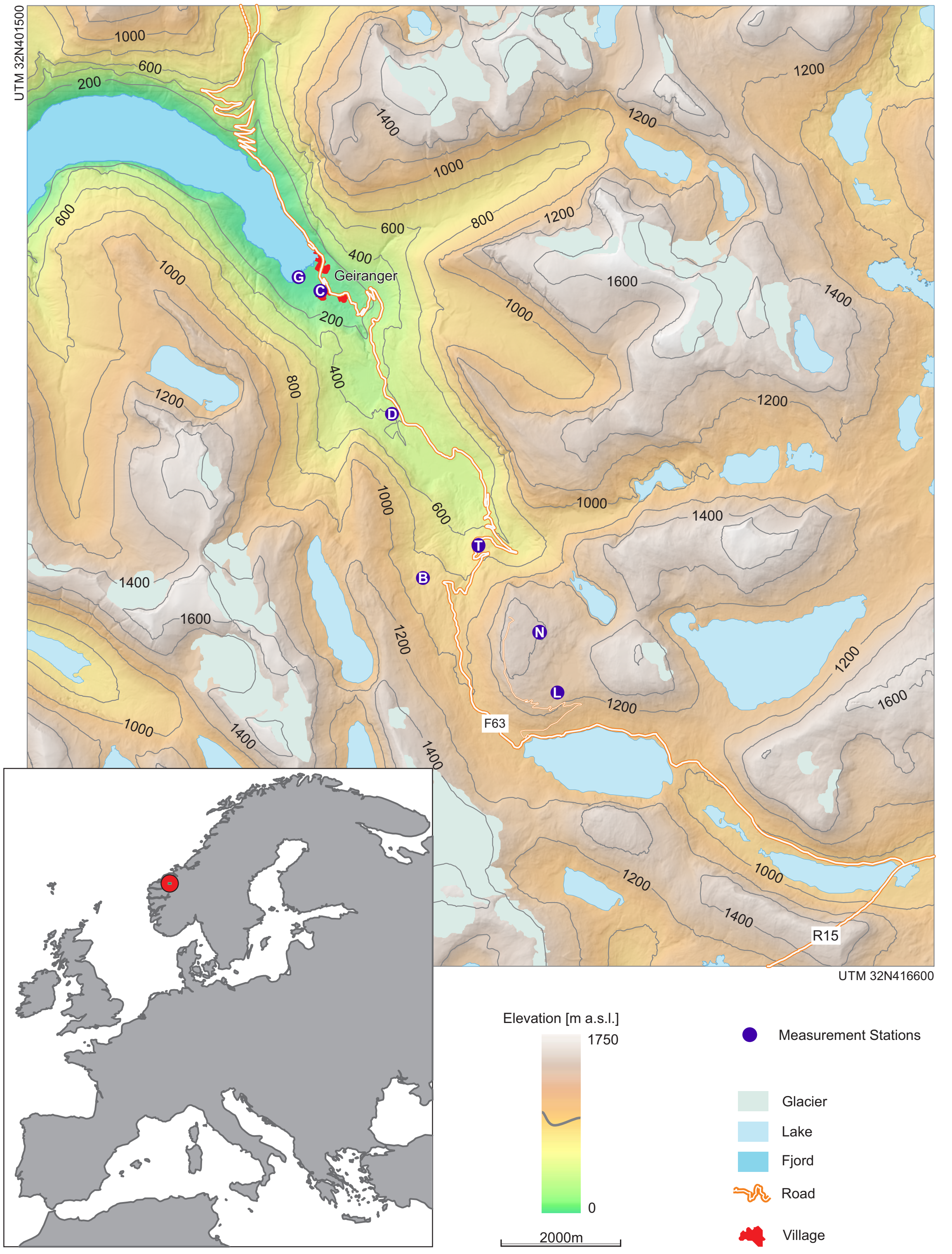

Fig. 1: Map of our study area and spatial arrangement of our measurement stations ($PM_{2.5}$, meteorological variables) along an elevational transect; G=Geirangerfjord at sea level, C=National Fjord Centre at 90 m a.s.l., D=Dalen at 420 m a.s.l., T=Tregrense at 770 m a.s.l., B=Blåfjell at 933 m a.s.l., L=Litledalsfjell at 1280 m a.s.l., and N=Nibbefjell at 1450 m a.sl. Map data source: ©Kartverket (https://www.kartverket.no).

which has already been focusing on the mountain climatology in the same area for more than 20 years (Löffler 2002). In this regard, we expanded our meteorological measurement stations from the LTAER-NO program from the middle alpine elevation level downwards along the valley to sea level (Fig. 1). Additionally, we established three permanent PM-measurement stations at 420, 90 and 0 m a.s.l. (Fig. 1) (due to necessary continuous 230 V power supply, the locations of our PM-measurement stations were restricted to 420 m a.s.l.). With this experimental setting, we were able to approach and understand the long-term spatiotemporal distribution patterns of PM in the lower air volume of the valley. Combined with our datasets of our meteorological stations, we approached the associated microclimatic processes and weather conditions along the entire elevational gradient of the valley. We initiated our air quality monitoring program in 2015, and the presented dataset here comprises measurements ranging from 01.07.2015 - 31.12.2022. We aim to successively update the database in the future.

Table 1 provides an overview of the specifications and variables of our meteorological measurement stations at 0 and 1450 m a.s.l. At sea level and 1450 m a.s.l., the sensors were mounted to ADL-MX data loggers. Both sensors recorded data at hourly intervals (means). At 770, 930 and 1280 m a.s.l., we additionally recorded air temperature at 1-min intervals using ONSET's HOBO logger type H21-002 and type S-TMB-002 temperature sensors (± 0.2°C accuracy) (cf. Dobbert et al. 2021), which were again saved as hourly means. Supplementary, global radiation was recorded at our station at 933 m a.s.l. (same sensors as in Tab. 1) and saved as hourly means. There were missing data due to problems with power supply. Nevertheless, the mean data availability of all meteorological variables was approx. 97%, with a highest fraction of missing data values of about 26% (min. WS at sea level).

PM measurements were taken with a dust monitor (TSI DustTrak DRX Aerosol Monitor 8534), which is a real-time photometer based on a light-scattering 90° laser. It simultaneously measures particle mass from 0.001 to 150 mg/m³ and the corresponding size fraction in the range from 0.1 to 15 µm. The size fractions are segregated in five different classes: PM_1 (≤ 1 µm), $PM_{2.5}$ (≤ 2.5 µm), $PM_{RESPIRABLE}$ (≤ 4 µm), PM_{10} (≤ 10 µm), PM_{TOTAL} (≤ 15 µm) (TSI 2022). The dust monitor equipment was calibrated at the TSI labs, after 6 months run time, each. Every device was regularly zero-calibrated with the provided default zero-calibration filter. We used a flow rate of 1.5 l/min,

Tab. 1: Specifications of our meteorological stations and the corresponding variables at sea level and 1450 m a.s.l.

Variable [unit]	Sensor	Position above ground (cm)	Accuracy	Available at 0 m a.s.l.	Available at 1450 m a.s.l.
Air temperature (T [°C])	Skye SKH 2065	200	± 0.2°C	Yes	Yes
Relative air humidity (RH [%])	Skye SKH 2065	200	± 2%	Yes	No
(min., mean, max.) Wind speed (WS [m/s])	Thies 4.3324.32.xxx			Yes	Yes
Wind direction (WD [0-360°])	Thies 4.3324.32.xxx			Yes	Yes
Air Pressure (AP [hPa])	Meier-NT-MNT10025		±237 0.01 hPa	Yes	No
Precipitation (P [mm])	Lambrecht-meteo-15189	100	± 2%	Yes	No
Global radiation (R [W/m²])	Silicon pyranometer (type S-LIB-M003)	1	± 10 W/m²	Yes	Yes

time constant of 5 seconds and log interval of 10 minutes aggregated to hourly means. Again, due to problems with continuous power supply, there were missing data during multiple time frames. However, the mean data availability of the entire PM dataset was approx. 76%.

To assess the spatiotemporal distribution of ship-related PM in our study area, we combined our observations (here: $PM_{2.5}$ and meteorological variables) with the actual marine traffic situation at the port of Geiranger, based on available arrival and departure times from several online resources. We incorporated the three different main ship types: cruise, ferry, and Hurtigruten. Hurtigruten are also cruise ships with the additional possibility of cargo that travel along the coastal route from Bergen to Kirkenes, and usually arrive at the port of Geiranger every year during the high season (2 June until 31 August). Their schedules varied little from year to year, so year-specific arrival times were used where available (FDN n.d., FWFF n.d., Hurtigruten AS n.d., Marinetraffic n.d., Norwayprotravel n.d., Stranda Kommune 2021). Since winter 2021 onwards, the coastal route is operated by two different shipping companies, of which one is using LNG and battery-powered ships. Consequently, their corresponding sailings were not considered here. The corresponding cruise ship schedules were available from the local port authority (Geirangerfjord Cruise Port 2015-2022). In a similar way, we referred to the required ferry schedules from public domains (Norway's Best 2018-2022, Fram Møre og Romsdal Fylkeskommune 2022). The ferry schedules for 2015 and 2016 were not available; hence, arrival and departure times were taken from 2017. There were two different ferries operating in the Geirangerfjord area, whose arrival and departure could not clearly be differentiated according to their schedule. To still consider their emission contribution, the power of both main and auxiliary engines were estimated from the average values of the two ships (Fjordfaehren n.d., Wikipedia 2022). The engine data of the Hurtigruten ships were available from public domains (Hurtigwiki 2023). Here, ship-specific schedules were only available for 2018 (Stranda Kommune 2021), 2020 (Marinetraffic n.d.), 2021 (FDN n.d.), and 2022 (FDN n.d., Hurtigruten AS n.d.). As such, we calculated a mean value for the power of both main and auxiliary engines for the remaining ship arrivals in 2015-2017 and 2019.

3 Data structure

Our dataset is organized according to the following attributes:

Date Time
Timestamp with hourly resolution, 0-24 h.

G_PM$_{2.5}$ [µg/m³]
$PM_{2.5}$ concentration at Geirangerfjord sea level (~0 m a.s.l.).

C_PM$_{2.5}$ [µg/m³]
$PM_{2.5}$ concentration at the National Fjord Centre (~90 m a.s.l.).

D_PM$_{2.5}$ [µg/m³]
$PM_{2.5}$ concentration at Dalen (~420 m a.s.l.).

G_AP [hPa]
Air pressure at Geirangerfjord sea level (~0 m a.s.l.).

G_P [mm]
Precipitation (only liquid) at Geirangerfjord sea level (~0 m a.s.l.).

G_WD [0-360°]
Wind direction at Geirangerfjord sea level (~0 m a.s.l.).

N_WD [0-360°]
Wind direction at a middle-alpine mountain top Nibbefjell (~1450 m a.s.l.).

G_mxWS [m/s]
Maximum wind speed Geirangerfjord sea level (~0 m a.s.l.).

N_mxWS_14 [m/s]
Maximum wind speed at middle-alpine mountain top Nibbefjell (~1450 m a.s.l.).

G_avWS [m/s]
Average wind speed at Geirangerfjord sea level (~0 m a.s.l.).

N_avWS [m/s]
Average wind speed at middle-alpine mountain top Nibbefjell (~1450 m a.s.l.).

G_mnWS [m/s]
Minimum wind speed at Geirangerfjord sea level (~0 m a.s.l.).

N_mnWS [m/s]
Minimum wind speed at middle-alpine mountain top Nibbefjell (~1450 m a.s.l.).

G_RH [%]
Relative humidity at Geirangerfjord sea level (~0 m a.s.l.).

G_R [W/m²]
Global radiation at Geirangerfjord sea level (~0 m a.s.l.).

B_R [W/m²]
Global radiation at low-alpine mountain top Blåfjell (~933 m a.s.l.).

N_R [W/m²]
Global radiation at middle-alpine mountain top Nibbefjell (~1450 m a.s.l.).

G_T [°C]
Air temperature at Geirangerfjord sea level (~0 m a.s.l.).

T_T [°C]
Air temperature at a mountain top near treeline (~770 m a.s.l.).

B_T [°C]
Air temperature at low-alpine mountain top Blåfjell (~933 m a.s.l.).

L_T [°C]
Air temperature at a mountain top in the transition zone between low-alpine and middle-alpine belt, Litledalsfjell (~1280 m a.s.l.).

N_T [°C]
Air temperature at middle-alpine mountain top Nibbefjell (~1450 m a.s.l.).

4 Dataset

To get an overview of the weather conditions at our study area throughout the course of the year, Figure 2 shows daily mean values of all measured meteorological variables differentiated by elevation, based on the entire dataset (2015-2022). The characteristic spatiotemporal patterns of several variables refer to the complex microclimate in the Geirangerfjord valley. It can be seen that both wind speed and wind direction were spatially opposed during large parts of the period. Particularly during summer time, low wind speed at sea level coincided with increased wind speed at 1450 m a.s.l. Calm wind in the lower parts of the valley point to inversion layer formation, which is of high interest in terms of understanding the $PM_{2.5}$ concentration patterns. In addition, the course of our temperature values indicates the existence of inverse atmospheric conditions at certain periods. The smaller the difference between the temperature values along the elevational gradient, the higher the likelihood for the occurrence of an inversion layer. Otherwise, the weather conditions at our study area were characterized by increased precipitation particularly during autumn, and rather dry conditions during summer. Global radiation started to increase in spring, reached its peak in summer, and significantly dropped in autumn and winter, following a typical trend for an area at such latitude.

Figure 3 shows the cumulative time (hours per day) ships spent at the port of Geiranger (A), and measured $PM_{2.5}$ concentrations (daily mean values) at 420, 90, and 0 m a.s.l. (B), each for the entire investigation period. The cruise ship traffic was most pronounced during the summer season with up to 40 hours of anchorage time, whereas significantly less ships made port in spring and autumn. While no cruise ships arrived during winter in the years 2015-2019, few ships made port in late 2021 (November, December) and early 2022 (March, April). A substantial decrease in cruise ship arrivals can be observed in the years 2020 and 2021, which was related to travel restrictions due to the outbreak of the coronavirus pandemic (cf. Mauren 2020). Except for some irregularities in 2020, Hurtigruten ships arrived regularly from June to August. The ferry operated mainly during the tourist season from April to October, and additionally in the winter period since the beginning of 2022. Measured $PM_{2.5}$ concentrations were highly variable in the course of the investigation period. Though it is visible that the concentration patterns generally followed the time ships spent at port, a certain spatiotemporal decoupling is indicated by increased $PM_{2.5}$ concentrations during off-season. The spatial distribution along the different elevation levels suggest that large parts of the lower valley troposphere were similarly affected by $PM_{2.5}$.

Figure 4 illustrates the situation as an example of cruise ship emissions into the small air volume at low elevations.

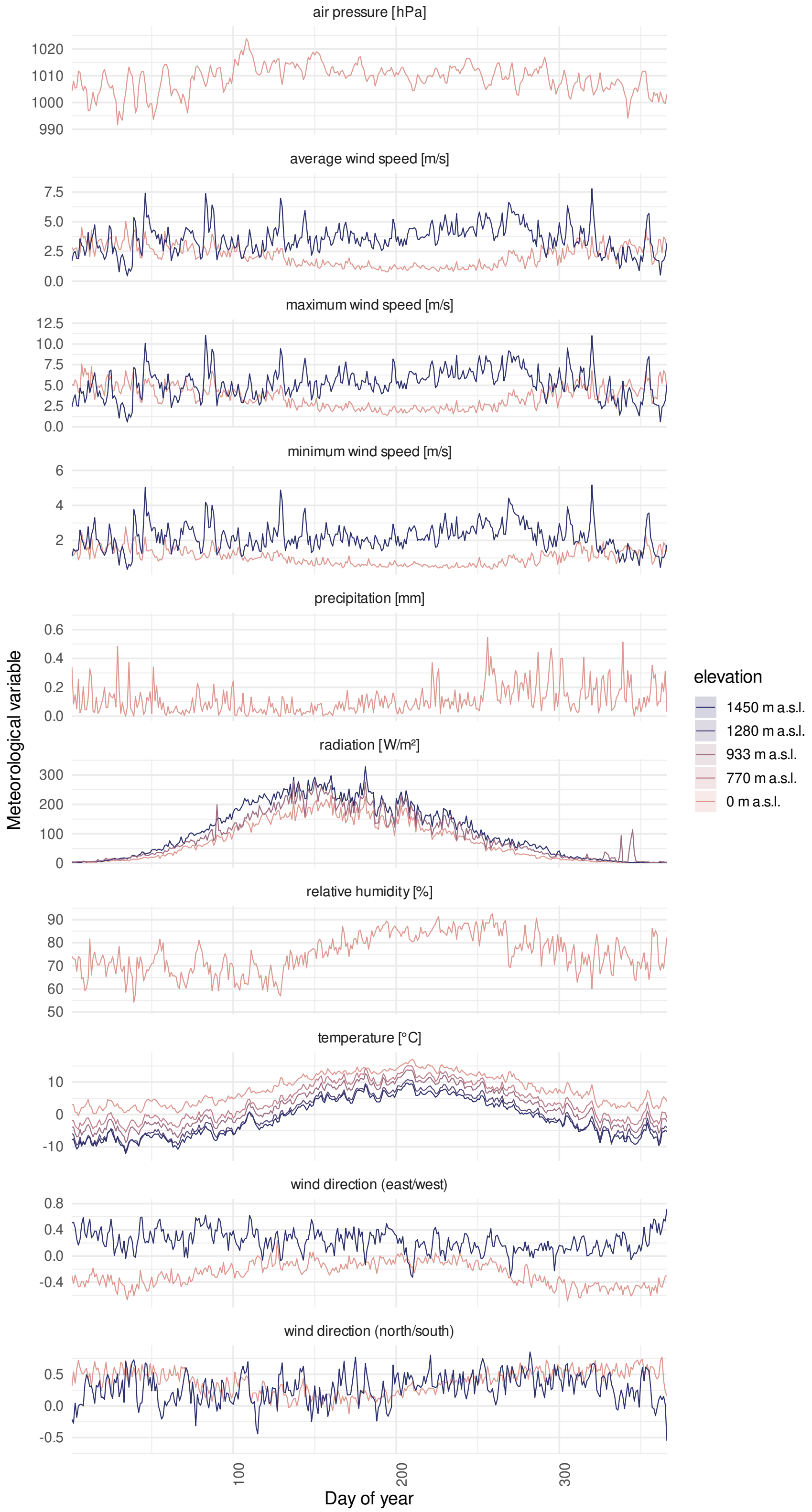

Fig. 2: Measured meteorological variables based on daily means of all years (2015-2022), differentiated by elevation

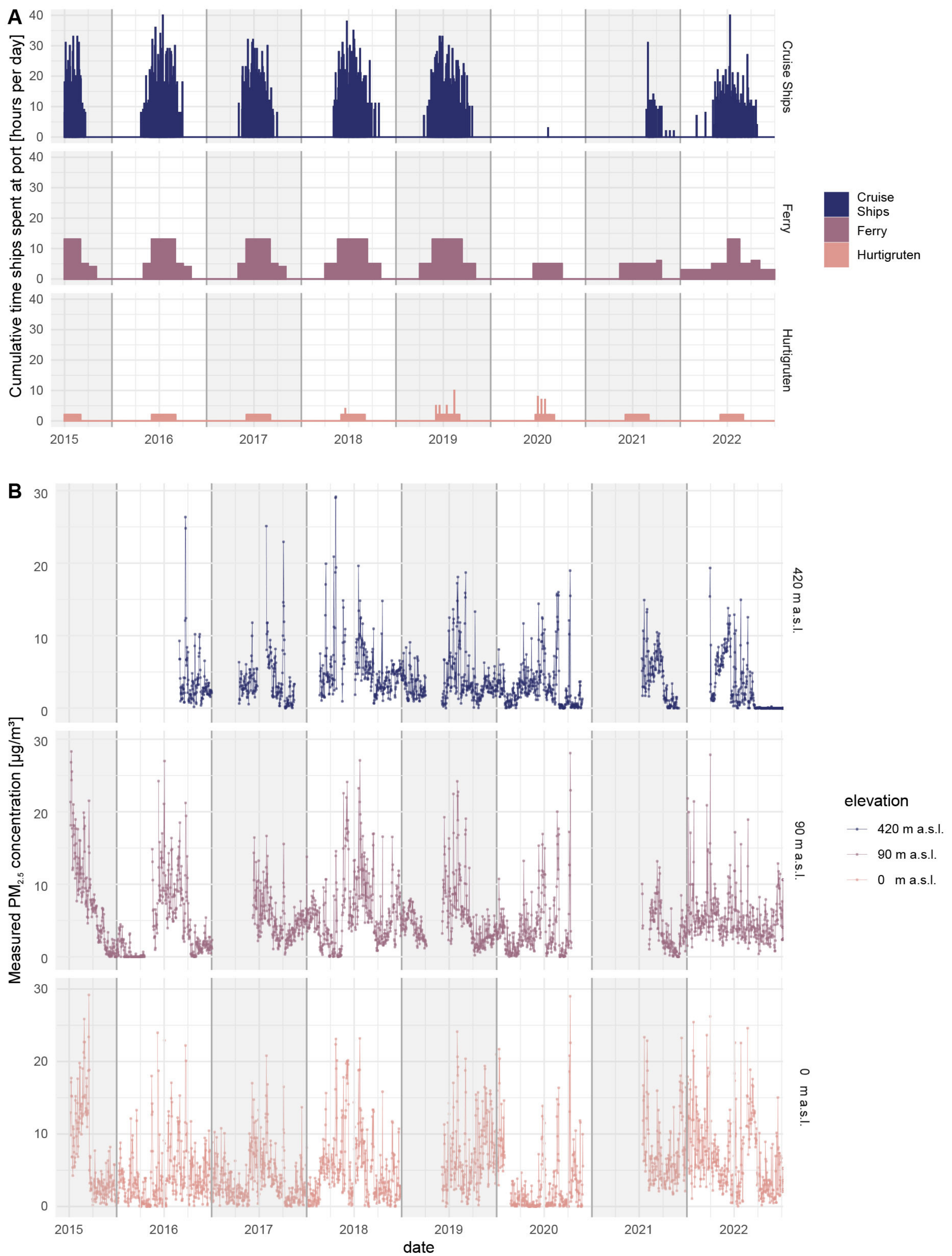

Fig. 3: Overview of the ship traffic (cumulative time ships spent at port [hours per day]) at our study area (A), and measured $PM_{2.5}$ concentrations (daily mean) at 420, 90, and 0 m. a.s.l. (B), each for the entire investigation period (2015-2022)

Fig. 4: View towards the port of Geiranger in the morning of 8 July 2022, with two cruise ships at berth. As particularly visible on the left side, vertical plume dispersion seemed to be hindered (approx. 200 m a.s.l.), which led to a rather horizontal distribution pattern of ship-related emissions.

Here, we publish our current dataset as part of an ongoing long-term project. This dataset will be updated, and is available as an online data supplement via the following link: https://doi.org/10.3112/erdkunde.2023.ds.03

Acknowledgements

We thank Katrin Blomvik Bakken and all members of the World Heritage Foundation Geirangerfjord for cooperation and overall support of the Long-Term Air Quality Monitoring Program. Further, we thank Rita Berstad Maraak (Stranda Havnevesen), Synöve Maråk, Wenche Dahl, Geir Gjørva, Lars Maråk. Our students contributed to our project during field courses and excursions. This work has been partially supported by MarineTraffic.

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